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The role of fire in U.K. peatland and moorland management; the need for informed, unbiased debate

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Abstract

Fire has been used for centuries to generate and manage some of the UK's cultural landscapes. Despite its complex role in the maintenance of U.K. peatlands and moorlands, there has been a trend of simplifying the narrative around burning to present it as an ecologically-damaging practice. That fire modifies peatland characteristics at a range of scales is clearly understood. Whether these changes are perceived as positive or negative depends upon the ecosystem service(s) and the spatial and temporal scales of concern. Here we explore the complex interactions and trade-offs in peatland fire management evaluating the benefits and costs of managed fire as they are currently understood. We highlight the need for (i) distinguishing between the impacts of fires with differing severity and frequency, and (ii) improved characterisation of ecosystem health that incorporates the response and recovery of peatlands to fire. We also explore how recent research has been contextualised within both scientific publications and the wider media and how these influence non-specialist perceptions. We emphasise the need for an informed, unbiased debate on fire as an ecological management tool that is separated from other aspects of moorland management and from political and economic opinions.

Introduction

Fire, either as a management tool or as wildfire, is a landscape-scale disturbance and a critical regulator of the ecological, hydrological and biogeochemical function of landscapes around the world (Pyne et al. 1996, Bowman et al. 2009, Fernandes et al. 2013, Ryan et al. 2013). This is the case in U.K. upland landscapes that notably include large areas of peatland. British upland ecosystems are highly variable in character and cover a spectrum of abiotic and biotic conditions reflecting the north-south temperature and east-west moisture gradients across the country. Peatlands include dry heaths on thin peats with vegetation dominated by *Calluna vulgaris* (L.) Hull (hereafter referred to as *Calluna*); similar vegetation on thinner organic soils that, due to their shallow depth, are not officially recognised as peat; wet heaths on peat dominated by a mixtures of *Calluna*, *Erica tetralix* L., grasses, sedges and *Sphagnum* spp.*;* and blanket bogs on deep peat which have a mosaic of vegetation communities that include some dominated by *Sphagnum* spp., *Eriophorum* spp., *Molinia caerulea* (L.) Moench, and other ericaceous species including *Calluna*. In the uplands such ecosystems are often collectively referred to as "moorland". Whilst in some northern and western regions these ecosystems may have a natural origin (e.g. Lindsay et al. 1988), in most locations they are the result of forest clearance and domestic livestock grazing that may date back thousands of years (Simmons 2003). Most moorland vegetation is highly flammable which favoured the use of fire as an important tool in their management throughout the past (Simmons 2003). Even vegetation on apparently very wet bogs can be burnt in the early spring prior to the green-up of vegetation despite standing water at the ground surface (Hamilton 2000). Today, managed burning is strongly associated with habitat management for red grouse (*Lagopus lagopus scoticus* Latham 1787) on privately-owned shooting estates. The current form of rotational patch burning associated with grouse moor management (Figure 1) has been utilised for roughly the last 200 years (Simmons 2003), though managed burning can be utilised to achieve a variety of ecological objectives (Davies et al. 2008). Fire was also an important component of the management of upland areas for cattle and sheep grazing prior to the popularisation of grouse shooting (e.g. Dodgshon and Olsson 2006) and its use may stretch back as far as the Mesolithic (Simmons 1990). This parallels traditional land-use practices of similar antiquity throughout oceanic regions of North-West Europe, including Denmark (Jonassen 1950), Norway (Kaland 1986) and Sweden (Romell 1952). That peatland ecosystems have long been modified by fire is thus widely recognised, indeed in some locations there is evidence that regular burning has enhanced the selection of fire adaptive traits in peatland plant populations (Vandvik et al. 2014). Against this historical context we now need to understand: 1) how the dynamic equilibrium that exists in all ecosystems subject to recurrent disturbance varies in response to different fire disturbance regimes; 2) the extent to which differing fire regimes may drive changes in ecosystem state; and 3) how ecosystem composition and state in turn affects the delivery of key ecosystem services.

Despite the complex, long-term role of fire in peatland management, there is a growing trend of simplifying the narrative around burning in the uplands of the U.K. This presents managed burning as an ecological practice that is only damaging and responsible for the poor ecological condition of many heathland and peatland ecosystems. For example, the recent report by the Adaptation Sub-Committee (ASC 2013) shows 27% of deep peat sites in England experience management burning but are not known to have been subject to any form of restoration action. Some media reports (e.g. Doward 2015) have presented this as meaning that burning has destroyed 27% of England's blanket bogs. Recent studies have also identified the presence of burning on upland landscapes as being detrimental to these environments (Brown et al. 2015a), or emphasise potentially negative consequences of burning particularly with regards to carbon storage (Douglas et al. 2015). This is despite strong potential benefits from using fire as an ecological tool in oceanic heathlands and peatlands of Britain (e.g. Thompson et al. 1995, Davies et al. 2008) and North-West Europe (e.g. Velle et al. 2014). The emphasis in both of the preceding sentences should be on *potential* because, overall, there is a paucity of evidence upon which to make informed decisions. Further, the way the debate is being framed is concerning; notably the lack of engagement with key concepts from fire ecology, and the sometimes provocative manner in which results are publicised by authors, their organisations and/or journalists. In our opinion, this reinforces the current, dominant narrative regarding burning in the U.K., one which lacks nuance and appears to be influenced by political and economic conflicts rather than ecological understanding. Choices for future management are simplified into not burning (or even banning burning) versus continuing an intensive, stereotypical form of traditional rotational heather burning. In reality existing practices are very spatially heterogeneous, and many good, as well as poor, examples of practice exist). The tone of the debate makes completing much needed further research problematic as land-managers are less inclined to collaborate when the prevailing public perception of fire is negative and managers themselves can view scientists as having an agenda.

Here, based on recent peer-reviewed literature on the use of managed fire in the U.K. uplands, and its subsequent presentation in the wider media, we consider there is an urgent need for researchers to:

1. Provide robust evidence of the interactions and trade-offs between the various practices associated with peatland management regimes (grazing, drainage, and fire).
2. Consistently classify the effects of all vegetation fires according to burn severity. At its simplest level this means not confounding severe wildfire effects with those from management burns. Management fires are set in winter or early spring when soil heating is minimal. In contrast, wildfires predominantly occur in spring and summer during dry periods (Legg et al. 2007) when deep soil heating and peat ignition are much more probable. There is a continuum of burn severity across both managed burns and wildfires and this varies temporally and spatially (Davies et al. 2014, Davies et al. 2016).
3. Develop appropriate guidelines for classifying peatland condition that account for their fire ecology
4. Generate informed and unbiased debate regarding peatland fire management that separates ecology from politics and economics.

Complexities in understanding the role of fire in peatland ecosystems

Interactions and trade-offs in peatland fire management

Any ecological disturbance has benefits and costs depending on the species or ecosystem in question. Where humans plan ecological disturbances for landscape management goals, it is essential to weigh up the trade-offs involved and make decisions that reflect the weighting given to different priorities. Fire is one such disturbance. In many ecosystems, fire is a natural process that plays a vital role in facilitating plant regeneration, defining vegetation community composition, controlling landscape-scale variation in habitat structure and modulating subsequent wildfire behaviour and severity (e.g. Pyne et al. 1996; Bowman et al. 2009; Belcher 2013). Managed fire superimposes or replaces natural fire regimes and reinforces ecological processes that depend on fire disturbance. Peatlands and moorlands in the U.K. are designated habitats, recognized for their conservation importance (Usher and Thompson 1993), but many are also cultural landscapes that owe their existence to the use of fire as a management tool (Simmons 2003). Fire has been, and still is, an integral part of the U.K. upland landscape. Effective landscape management that uses fire as a tool needs to utilise it in a sustainable manner, integrating traditional approaches where necessary, to maximise the desired ecosystem benefits or services and minimise disbenefits (Fernandes et al. 2013). This will require an evidence-based approach adapted to suit local conditions, with some managed fire regimes better able to minimise trade-offs than others (no one size fits all). Previous authors (e.g. Usher and Thompson 1993, Thompson et al. 1995, Davies et al. 2008) have suggested that such an approach could include: a reduction in the frequency of burning over blanket bog; a reduction in average burn size and increased variation in burn area to produce a more heterogeneous mosaic; a reduction in the proportion of moorland burned and a greater amount of unburned heather; a shift in vegetation succession towards scrub on suitable parts of moorland (e.g. steep slopes); and maintaining fire-free buffers around riparian systems. There is also evidence that burning may not be required to maintain *Calluna* productivity in all situations. Results from the study by MacDonald et al. (1995) show that *Calluna* can regenerate by "layering" and the formation of adventitious roots. This led to the recommendations that managers do not burn stands which have not experienced fires in the last 40 years and which have well developed heather layering; avoid burning *Calluna* in wet, shaded or humid situations where layering is likely; and concentrate burning activity where *Calluna* forms dense, continuous stands. Whilst these management suggestions may seem like common sense to many, there remains surprisingly little scientific evidence to suggest what their outcomes would be in terms of patch or landscape scale ecosystem structure, function or diversity.

It is not our aim here to provide an exhaustive review of the effects of fire on peatland environments or other ecosystems. Instead we suggest readers refer to holistic reviews of the effect of fire on the environment (Neary et al. 2005), and specific reviews of the effects of fire on soils (Santin and Doerr, this issue), peatland ecosystems (Turetsky et al. 2015; Worrall et al. 2010), carbon and climate (Sommers et al., 2014), human health (Johnston et al., this issue) and U.K. moorlands (Glaves et al. 2013). It is however informative to draw attention to a number of recent, relevant studies that highlight the range of potential outcomes from burning. Within the diverse spectrum of fire effects, managed burning can have a range of potential benefits for peatland management, for example, removing dense canopies of *Calluna* via burning creates hydrological and light conditions that favour *Sphagnum* species over pleurocarpous mosses. Evidence from fire-prone black-spruce forested bogs in North America and mires in Sweden, for example, show that *Sphagnum* species are replaced by pleurocarpous mosses under dense canopies that can be removed by wildfire (Gunnarsson et al. 2002; Benscoter and Vitt 2008). Experimental studies have shown that *Sphagnum* plants can regenerate from deeply buried stems (Clymo and Duckett 1986) and in boreal systems *Sphagnum* plants have been observed to vigorously resprout following intense wildfires (Benscoter and Vitt 2008). Reductions in *Calluna* canopy density are likely to be required to restore peat-forming vegetation on many degraded bogs, and fire may be an effective way to achieve this particularly if the *Calluna* is old and unlikely to resprout (Davies et al. 2010). Evidence from the U.K.'s only long-term replicated burning experiment shows positive effects of controlled burning as *Sphagnum* abundance was higher in 10-year burn rotations than in both

20-year rotations and locations that had not been burnt for ~90 years (Lee et al. 2013). This result, perhaps surprising to some, is reinforced by other studies showing rapid recovery of *Sphagnum* populations following managed fires (e.g. Hamilton 2001; Taylor 2015) and that, in laboratory experiments, even prolonged exposure to high temperatures can be followed by *Sphagnum* resprouting, i.e. high temperature alone does not kill the entire *Sphagnum* plant (Taylor 2015). Based on this research, it appears hummock-forming species such as *Sphagnum capillifolium* (Ehrh.) Hedw, and *Sphagnum fuscum* (Schimp.) H. Klinggr are particularly resilient to fire, but data are needed on burn effects on other species.

Managed burning can have additional benefits and previous authors have documented the potential for a positive relationship between the use of fire and the diversity of vascular plants (Harris et al. 2011) and lichens (Davies and Legg 2008), as well as populations of invertebrates (Buchanan et al. 2006) and other wildlife, though the relationships are often complex. For instance, Davies et al. (2008) showed that post-fire trends in abundance differed between lichen species meaning the benefits of burning for diversity were recognised at the landscape scale due to the associated heterogeneity in stand ages. Bargmann et al. (2015) noted similar results for carabid beetles but also showed particularly high alpha diversity in recently burnt stands. In the study by Tharme et al. (2001), whilst red grouse and golden plover (*Pluvialis apricaria* L. 1758) populations were positively affected by prescribed burning, meadow pippits (*Anthus pratensis* L. 1758) were negatively impacted. Elsewhere in Europe, researchers have shown the benefit of prescribed fire use in preventing the loss of protected, internationally rare moorland ecosystems more generally (e.g. Vandvik et al. 2005; Ascoli et al. 2009; Alday et al. 2013; Hornman and Haveman 2001), and in promoting seed regeneration and diversity of ecologically and geographically restricted species (Velle et al 2014 a,b). Recent modelling work suggests that short-rotation prescribed moorland burning also minimises direct carbon loss from combustion that could otherwise occur under a more severe wildfire regime (Allen et al. 2013). Furthermore, burning can also produce substantial quantities of carbon in refractory forms, which contributes to the longer-term carbon sequestration potential of moorlands (Worrall et al. 2013; Santín et al. 2015).

Against this backdrop of the potential positive effects of managed burning in the U.K. and elsewhere the rhetoric against burning in the U.K. may seem odd. However, notwithstanding these desired, positive effects, regular managed burning is also associated with negative impacts. These include evidence for altered stream water chemistry including increased dissolved organic carbon (DOC) production (e.g.

Rachmunder et al. 2013) that may indicate wider changes in carbon storage and which has financial implications for utility companies due to the need to treat colouration of drinking water from upland catchments. Rachmunder et al. (2013) showed that streams draining catchments that were managed using burning contained increased particulate organic matter, suspended sediments, and aluminium, iron and DOC than unmanaged (non-burned) catchments. The differences in water quality were associated with major differences in benthic macroinvertebrate community structure. However, there is also contrary evidence on the production of DOC including that, i) prescribed burning is associated with changes in DOC quality, and associated water colouration, rather than DOC quantity (Clay et al. 2012); ii) that DOC is strongly associated with the dominance of *Calluna* rather than burning per se (Armstrong et al. 2012; Holden et al. 2012); and iii) in Sweden (and elsewhere) increased discoloration of water also occurs in areas without moorland burning and the levels could not be attributed to organic carbon alone (Kritzberg and Ekstrom 2012; Ekström et al. 2011). There the prevailing hypothesis is that the coloration results from decreased acidification. Furthermore, as has been noted elsewhere (Clay et al. 2012; Holden et al. 2012) there is a disconnect between the direction and magnitude of DOC changes between plot scale studies (e.g. Clay et al. 2009) and catchment level monitoring (e.g. Clutterbuck and Yallop 2010). Further study is required to couple the processes between these two scales. Some authors have also questioned whether increased DOC transport offsite leads to net C loss or simply serves as a conveyer for some of it to be accumulated elsewhere (Jaffe et al. 2013). In-stream degradation processes (e.g. photo-induced degradation, Moody et al., 2013) will also determine whether there will be a lag between export and the transfer of carbon to the atmosphere. Thus it is likely that some prescribed burning regimes have an effect on DOC in some places, but the picture is far from simple.

Rates of peat accumulation have been noted to be lower in areas burnt by management fires (Garnett 1998; Garnett et al. 2000) suggesting that in terms of carbon sequestration burning may not be beneficial. However, Garnett (1998 and 2000) examined only the shorter (10 year) burning rotation at the long-term Hard Hill experiment site (further described below) and thus the evidence may not be comparable to most prescribed burns on peatlands which typically occur at longer intervals. There are few complete carbon budgets from U.K. peatland sites subject to management burning, but some studies have indicated that managed fire may lead to an ‘avoided loss’ of carbon (Clay et al. 2010a; Clay et al. 2015) where burnt plots are smaller sources of carbon than unburnt controls. However, at no time did the management interventions in those studies lead to a transition to a carbon sink. Evidence for the effects of fire on the microbial community are scarce and tend to come from wildfire studies rather than prescribed burning, but perturbation by fire may stimulate microbial activity within peat and increase the rate of decomposition (Maltby et al. 1990) impacting carbon storage. The effects on the microbial community may also be persistent (Zenova et al. 2008) and involve changes to methane oxidation processes (Jaatinen et al. 2004) and substrate use by the soil microbial community (Bergner et al. 2004). Prescribed fire can also cause changes to soil temperature regimes (Grau et al. 2014; Brown et al. 2015b) with likely effects on process such as peat respiration, methanogenesis and methanotrophy (Limpens et al. 2008). Taken alone the alterations to peat temperature regimes recorded by Grau et al. (2014) would suggest likely increases in soil C fluxes. Although many studies have shown that peat temperature is a critical control on microbial activity (e.g. Scanlon 2000), recent studies demonstrate that above and below ground systems are highly coupled and alterations to vegetation structure, as can be caused by burning, must also be considered (Walker et al. in press)

Other impacts of long-term use of prescribed burning on the peatland terrestrial habitat may include a lowered water table and lower pH (Brown et al., 2014), changes to soil water chemistry (Clay et al., 2010b), and impacts on nutrient availability. Earlier research suggested that there may be long-term depletion of N, P and K (Elliott 1953) associated with managed burning. Subsequent studies concluded that these nutrient losses were replaced through precipitation (Allen 1964, Robertson and Davies 1965, Tucker 2003), but more recent work has again suggested that N can be lost during prescribed burning (Rosenburgh et al. 2013). The case of nutrient dynamics is, actually, a very interesting one as it nicely illustrates some of the complexities involved in categorising fire effects as damaging or otherwise. Although losses of macronutrients may be easily perceived as a negative outcome of fire, nutrient deposition from atmospheric pollution has been one of the key drivers of degradation in blanket bog and heathland communities both within the U.K. and elsewhere in Europe (Holden et al. 2007). Management activities that reduce nutrient availability in what are, by definition, low nutrient systems may actually be beneficial for the recovery of key peatland species, such as *Sphagnum*, which are highly-sensitive to increased nutrient loadings (Phoenix et al. 2012). In this regard, the conclusions of Rosenburgh et al. (2013), that large N inputs added via atmospheric pollution and subsequent soil N saturation can be alleviated by prescribed burning, are welcome.

Prescribed fire also has the potential for negative interactions with other land management practices - especially drainage and grazing (e.g. Stevenson and Rhodes 2000). However, evidence for this is still rather patchy. For example, despite much research on the effects on heathland vegetation, evidence for vegetation succession pathways in response to combinations of burning, grazing and drainage in the U.K. uplands largely remains hypothetical particularly for peatlands (c.f. Thompson et al. 1995, Shaw et al. 1996). Often studies are unable to untangle complex interacting disturbances: the paper by Bludnell and Holden (2015) for instance ascribes the loss of *Sphagnum* cover in a single case-study catchment to repeated severe wildfires but ascribe its lack of recovery on managed burning. However, they also acknowledge that subsequent nutrient and acid deposition from air pollution may also have been important. In aerial photographs the area they studied (Lat 53.853033, Long: -2.028975) shows extensive evidence of gullying and it is unclear whether this is related to a transition in the site's hydrological and ecological state following the compounded severe wildfires. When burning, grazing and drainage are carried out indiscriminately, these management practices are likely to be damaging blanket bog and may even lead to loss of habitat (Shaw et al. 1996) and carbon.

Understanding fire regimes – the importance of fire severity

Whilst the effects of prescribed burning demand that we make trade-offs between different ecosystem services, there is growing evidence and consensus that severe, uncontrolled wildfires can have very serious consequences. Under drought conditions, wildfires can ignite peat layers causing smouldering peat fires and large emissions of carbon to the atmosphere (Davies et al. 2013; Turetsky et al. 2015). Severe smouldering peat fires also have the potential to mobilise legacy pollutants in organic soils through volatilization or subsequent erosion (e.g. mercury, Turetsky et al. 2006; lead, Rothwell et al. 2007) which is of particular concern in heavily polluted peatlands in some areas of the UK (e.g. Peak District National Park, Shuttleworth et al. 2015). Even where peat itself is not ignited, severe wildfires show very different rates of ground biomass (moss, litter and duff) consumption compared to prescribed burns (Davies et al. 2016) and are potentially associated with changes to soil carbon dynamics (Davies et al. 2014). Severe wildfires over organic soils can also produce a hard, hydrophobic bitumen surface that leads to increased runoff and changes to peatland hydrology with dramatic consequences for vegetation succession (Maltby et al. 1990; Legg et al. 1992). Severe wildfires have also been associated with lower rates of peat accumulation than unburnt areas (Kurhy 1994) and the loss of *Sphagnum* cover (Blundell and Holden 2015). We re-emphasise that the effects of severe wildfires should be separated from the outcomes of a carefully-managed prescribed burn, and that the ecosystem outcomes of fire differ with wide variation in fire severity. Davies et al. (2010, 2014) for instance, show that, during managed fires, consumption of the layer of moss and litter that overlies and protects the peat surface during burning is never more than ca. 20% of the pre-fire mass, and that bare-peat substrates following burning are the exception rather than the rule. Furthermore, Davies et al. (2016) and Clay and Worrall (2011) demonstrate that there can be very considerable variation in fire severity between and within individual wildfires. As we will highlight below, deliberately or accidentally confounding the effects of severe wildfires with those of low-severity prescribed burns (or even low severity wildfires) can be very misleading.

Understanding fire regimes – the importance of fire frequency

The effects of fire vary both temporally and spatially with associated benefits and disbenefits depending on the scale one considers as well as the ecosystem services one is most interested in. Some changes are associated with the immediate aftermath of a fire (for example changes to peat temperature regimes), whilst others (e.g. alterations to vegetation community structure) may only become apparent by taking a longer-term perspective. Fires vary in both their intensity and severity, which is the result of spatial variation in vegetation/fuel structure and climate, temporal variation in fire weather (especially fuel moisture) between and within seasons and, in the case of prescribed burns, the expertise and care with which burns are managed. It is only by understanding the overall character of current and historic fire regimes (*sensu* Davies 2013) that one can draw robust conclusions about the ecological effects of fire. In the U.K. such information is conspicuous by its absence. A few trends have, however, been noted. Most managed burning in the U.K. is focused in core areas for grouse moor management in the Pennines, North York Moors and Grampian regions (Douglas et al. 2015). In these regions, fires on heather moorlands are recommended to be burnt on a rotation that would, very roughly, equate to a fire every 10-25 years (Scottish Government 2011). It has been suggested that such burning activity has been increasing within the Peak District (Yallop et al. 2006) and nationally (Douglas et al. 2015), whilst other, older research indicated that the use of fire as a management tool may be declining in Scotland (Hester and Sydes 1992). Some of us have previously argued that such studies may be misleading and that less subjective methods are needed to map burning extent (Davies et al. 2016). Crucially, none of the methods of estimating management history from aerial photographs used in these studies have received any form of ground-truthing though more recently Allen et al. (2016) compared some of their results with estate managers' maps of burning activity. Nevertheless, the national mapping study of Douglas et al. (2015) is one of the best we have. They used visual inspection of aerial photographs to define areas of *Calluna*-dominated vegetation and mapped burning within such communities. Taking their estimates of a mean proportion of moorland burnt in the U.K. during the last 25 years (16.7%), the annual percentage area burned and mean fire rotation can roughly be estimated (*sensu* Romme 1980).

This results in 0.68% of moorland in Great Britain being burned per year (range 0.04% – 3.8%) and an average fire return interval of 147 years (range 26 – 2,500 years) - assuming repeat burning within 25 years does not account for a significant area (the study by Allen et al. (2016) suggests this is fair for at least some regions). Though these are very rough estimates, they suggest considerable heterogeneity in fire regimes across the British uplands, with the majority of sites likely experiencing fire return intervals rather longer than the 10-20 years traditionally recommended for heather moorlands. This concurs with the results of Allen et al. (2016) who showed that, for a case study area within the Peak District, most burning followed recommended guidelines for fire frequency and fire size. The fire rotation values we estimate here are comparable to, or longer than, those associated with other peatland ecosystems where fire is a natural disturbance. For example: Vandvik et al. (2014) summarised natural fire return intervals in Norwegian boreal heaths and forests ranging between ca. 100 – several thousand years (the latter being rare); Wieder et al. (2009) documented fire return intervals of 123 ± 26 years in black spruce bogs in North American boreal forests. Yet, whilst fire frequency within landscapes is important, it is not the only variable of relevance in understanding the overall effect of fires. Rather we need to quantify variation in the entire fire regime (Davies 2013) which not only includes fire frequency, but also fire intensity (rate of energy release during combustion), severity (immediate ecosystem effects such as vegetation consumption by the fire and sub-surface heating), extent, seasonality and spatial and temporal variability in these attributes.

Monitoring peatland ecological condition in relation to fire

Despite the central role of fire in the ecology of U.K. peatland and moorland ecosystems, and the promotion of fire use for restoration of similar ecosystems in both southern (Fernandes et al. 2013) and northern (e.g. Velle et al. 2014a) European countries, there is growing pressure to significantly reduce or even ban burning. Attention is often drawn to the fact that burning causes peatland ecosystems to be in "unfavourable condition" (JNCC 2009). However, this notion results from standardised assessment criteria that implicitly assume that fire only has damaging effects on peatlands and that, therefore, do not account for the fire ecology of our upland landscapes. The guidelines for Common Standards Monitoring practices (JNCC 2009) on peatlands in U.K. protected areas thus make it more-or-less impossible for burned sites to be classified as being in good condition (Box 1), despite the potential ecological benefits of prescribed fire. Essentially, the presence or evidence of fire is a "fail" criterion even when prescribed fire is part of an approved management agreement. As Yallop et al. (2006) suggested this inflates estimates of the impact of fire by assuming the whole site is affected by burning but also ignores any beneficial effects of fire. This monitoring therefore provides potentially misleading information as large areas of peatland are recorded as degraded simply because they have experienced fire (JNCC 2009). No attention is given to the nature of the burns or the character of the fire regime at the site.

Generating informed, unbiased debate about the ecology of fire

Contextualisation of fire research within academic literature and beyond

Prescribed fire provides an array of management benefits and challenges within a U.K. context that vary depending on the prioritised ecosystem services. Research has a key role in informing scientific, policy and public perceptions and debates on appropriate prescribed fire use. The interaction between research outcomes and society for a large part occurs through the public media. Whilst science communication represents a difficult process of distilling technical research findings and complex messages into simplified media stories, effective and accurate communication is essential if appropriate land and fire management strategies are to be implemented. Unfortunately, the way in which research is presented in the media is not always unbiased and research can be manipulated or misinterpreted by persons or groups that may have a pre-determined agenda. We emphasise the challenges of such debate through the discussion of recent case studies (Yallop et al. 2006; Brown et al. 2015a; Douglas et al. 2015), some of which were highly publicised within the U.K. media. Through these case studies, we highlight how the scientific position can become skewed both within scientific publications themselves, and in their subsequent representation within the media.

Representation of fire in scientific publications

The context set by Yallop et al. (2006) is a relatively balanced discussion of benefits and costs of managed fire, except for the fact that for some research areas they consider the evidence base to support their assertions was rather limited. This was (and still is) particularly true for the effects of fire on carbon sequestration. Yallop et al. (2006) cite one paper where managed burning was shown to reduce carbon sequestration in peat bogs (Garnett et al. 2000). However, Garnett et al (2000) were unable to examine the effects across all replicates and treatments at their Moor House Hard Hill experiment and hence their experiment lost the power of the replicated experimental design. It is also evident that for much of Yallop et al's carbon-focused discussion there is a reliance on wildfire papers from boreal studies outside the U.K. (e.g. Kuhry 1994; Pitkänen et al. 1999). This is undoubtedly a consequence of the lack of local evidence in this research area, but there is no clear acknowledgement of this carbon knowledge-gap or how it impacts the scientific debate being put forward. This seems a relatively important point given the way the media picked up on their study, choosing to concentrate on burning impacts on peatland carbon emissions rather than the mapping exercise the paper was concerned with (see *Representation of science within the media*).

The study of Douglas et al. (2015) sets a context in which the effects of fire on the natural environment are primarily negative. Whilst initial mention is made of potential positive benefits of burning, the authors go on to question the widely accepted benefits of prescribed fire for wildfire hazard reduction (Stephens et al. 2009, Fernandes et al. 2013, Ryan et al. 2013), citing Altangerel and Kull (2013) and suggesting that "the benefits and disbenefits [are] debated". In reality, Altangerel and Kull (2013) themselves conclude that "*differences in how people frame the risks of prescribed burning, the certainty of its outcomes and what values they evoke in order to justify their views do not necessarily arise from divergent priorities about nature, people or assets, but instead from contrasting views about whether humans or nature are voluntarily or involuntarily exposed to wildfire risk*". Thus the debate is not so much about the effectiveness of fire as a tool but rather about the societal responses to its use. Interestingly, Altangerel and Kull (2013) point out that both citizen groups in favour of, and against, prescribed burning tend to selectively frame their arguments to build support for their views.

Douglas et al. (2015) refer to "*increasing evidence of negative environmental impacts of burning*" across "*a range of systems*". A number of papers or reports are cited to suggest negative impacts of fire on soil erosion (Cawson et al. 2012), nutrient cycling and soil hydrology (Neary et al. 1999), water quality (Battle and Golladay 2003), air pollution (Tian et al. 2008) and *Sphagnum* plants (Brown et al. 2014). However, this fails to recognise the complex messages from each of these studies in which clear benefits of fire management could also be highlighted. Cawson et al. (2012) showed that catchment-scale studies usually report minimal impacts of prescribed burning on post-fire runoff and erosion from mineral soils. They stressed the importance of understanding how fire characteristics affect post-fire runoff and erosion, as fire regimes can be manipulated to reduce potential erosion and water quality impacts. Neary et al. (1999) reviewed the direct effects of fire on below-ground systems (mostly mineral soils) and described them as a function of burn severity, which integrates aboveground fuel loading (live and dead), soil moisture, duration of the burn and post-fire soil temperatures. Tian et al. (2008) assessed atmospheric emissions of prescribed burns and showed that corresponding air quality impacts can be mitigated by forest management practices. For example, where prescribed burning is less frequent, increasingly more fuel is burnt in each fire, leading to higher emissions and greater air quality impacts per fire. Brown et al. (2014) is cited to support the argument that fire has a negative impact on *Sphagnum* plants, but the focus of this report is on aquatic ecosystems and catchment hydrology; the authors make no direct observations of fire's impact on *Sphagnum* itself and this assertion is in conflict with the results of Lee et al. (2013). Further, Douglas et al. (2015) contextualise their research within the debate about the relationship between fire and peatland carbon dynamics. Despite this, many of their assertions are not currently supported by scientific consensus, which is partly demonstrated by their reliance upon unpublished or non-peer reviewed reports (e.g. Lindsay 2010; Brown et al. 2014). This highlights an important issue, where the fire evidence base is weak, grey literature can often be the only source of evidence. Whilst grey literature is used in scientific evidence reviews and meta-analyses to counter publication bias (Haddaway and Bayliss 2015) one aspect of using it authors should perhaps attempt to avoid, is the tendency to cite without critical assessment. For example, Brown et al. (2014) do not include any fire ecology measures (e.g. severity) and lack a detailed description of the statistical models used in their analyses. Their experimental design is fairly complex, including fire chronosequences and different sampling intensities across certain sites. A lack of statistical methodology makes scientific evaluation of their findings problematic (Haddaway and Verhoeven 2015). This point was not highlighted in Douglas et al. (2015), and unfortunately, a critical and balanced assessment was also lacking from the resulting inflamed media reports that followed Brown et al. (2014) (see Table 1). Although a proportion of the results presented in Brown et al. (2014) have now been published in peer-reviewed journals, it would have been preferable to have published a report that could be scrutinised in more detail and to have subjected findings to peer review before releasing the summary report.

Brown et al. (2015a) reviewed the impacts of fire on the hydrology, biogeochemistry, and ecology of peatland river systems and gave a relatively thorough overview of the limited existing evidence of the changes that burning can induce in hydrological and aquatic systems. In some places however their discussion appears to restate popularly-held but unsupported assumptions and to rely heavily on unpublished material. For instance, in the section of their paper concerning fire effects on terrestrial vegetation, they state "*Burning is considered particularly detrimental to peat-forming Sphagnum species*" but the citation to support this assertion is an unpublished report by the Royal Society for the Protection of Birds (RSPB). They also point to government guidelines that "*recommend against burning into living moss layers*" but then comment that "*this level of control is not always achievable*".

Notwithstanding the fact that the fuel moisture content of moss layers during the legal burning period are often high enough to make deep combustion physically impossible in all but the most severe droughts (Legg et al. 2007), there is good evidence that moss consumption during prescribed burns is very limited (Davies et al. 2015) and that exposure of bare peat is rare (Davies et al. 2010). Where Brown et al. (2015a) suggest burning leads to peat exposure their citations relate to the outcomes of severe wildfires rather than prescribed burns. They, therefore, make the common mistake of conflating fire intensity and degree of control with fire severity, when in reality the link between intensity and severity is complex (Davies et al. 2010; Davies et al. 2015; Davies et al. 2016). Whilst Brown et al. (2015a) are right to point out that burn management is sometimes far from perfect, we still have very little data on how management practices vary across the U.K. and again need to realise that the issue in question is not as simple as burnt/unburnt but rather how ecosystem changes scale across variation in fire regimes (i.e. frequency, extent, intensity, severity, seasonality and variability in these).

Finally, Brown et al. (2015) rightly point out that much of our knowledge comes from a single long-term experimental study site (the Hard Hill burning/grazing experiment in Cumbria, England), but then they seek to suggest (again on the basis of an unpublished RSPB report) that the results from that location are not generalisable as the fires are "*extremely controlled*"; despite the fact that the use of controlled fire is precisely the aim of prescribed burning. As far as we are aware, no data has actually been published on prescribed burning practices at Hard Hill or the behaviour of the fires burnt there. Furthermore, the inference that at all other sites fire conditions are not 'extremely controlled' would perhaps imply that moorland managers are either not very good at, or do not care about, adequate fire control. In reality, it is in the interests of managers to ensure fires do not grow too large or intense such that they would destroy the habitat matrix grouse require, or such that they put *Calluna* regeneration at risk. Further data on variation in prescribed burning practice (e.g. average fire size, orientation along slopes, spatial distribution within landscapes in relation to sensitive areas such as scree or riparian zones) would be welcome. The results of Allen et al. (2016) show that, at least in their study area, practice meets existing guidelines and fires are well-controlled.

In summary, these three case studies create an unbalanced tone in which the outcomes of fire are presented as generally negative. Of course it is clear that episodic disturbances can induce significant changes in a range of environmental parameters, and that variation in disturbance regimes can drive changes in ecological structure and function. Whether these changes/differences are positive, negative or of no consequence is likely to depend upon the spatial and temporal scales, and ecosystem services, one chooses to focus on. A significant issue with all three case studies is that some of the evidence upon which they base their assertions is limited or incomplete, and following the citation trail often reveals insufficiently critical reliance upon either unpublished reports or a simplistic (mis)interpretation of complex scientific findings.

Representation of science within the media

The use of fire as a management tool within the media often appears to similarly lack nuance. A recent newspaper article by Monbiot (2016), provocatively titled "*Meet the conservationists who believe that burning is good for wildlife*" with the sub-heading "*Our national park authorities are vandals and fabulists, inflicting mass destruction on wildlife and habitats, then calling it conservation*", emerged whilst this paper was in review and is only the latest in a line of somewhat unhelpful contributions. With regards to the papers we assessed above, for both Yallop et al. (2006) and Douglas et al. (2015), the subsequent reporting in the media from associated press releases unfortunately did not focus on the strengths of their research findings. Instead the press releases used the papers as an opportunity to make tangential and provocative inferences about associated issues. The almost hysterical headlines of some news items were particularly striking (Table 1). The tone of many of these articles was staunchly anti-burning and focused on purported negative impacts of fire, even if this bore little relationship to the studies' actual focus. Many media articles concerning managed burning appear to be highly biased. For example, in the case of Pearce (2006, a magazine article) the focus, carbon losses as a result of burning, was not measured in the work reported by the scientific paper on which it was reporting (Yallop et al. 2006), and the quotes and narrative it contained were highly speculative. In the case of Doward (2015, a newspaper article), the news item suggested that research conflicting with the main anti-fire narrative was influenced by its funding source (The Game and Wildlife Conservation Trust, an organisation that has a large number of members active in game management or hunting, but which is also a well-regarded research and conservation charity).

Unfortunately, as scientists we often have little control over the representation of our research within the media. Others have noted how the characteristics of scientific claims change between scholarly writing and non-specialist audiences (Fahnestock 1986), and this is likely to remain a problem when journalists, unlike scientists, routinely refuse to allow pre-publication review of their articles even by those whose research they are covering. Despite this, the tone with which scientific output is covered in the media can be moderated through careful positioning of the research within the academic literature and in any associated press releases. We have no access to press releases from the publication of Yallop et al. (2006), but in our view the three different press releases associated with the Douglas et al. (2015) paper (RSPB, 2015a,b,c) bear only passing resemblance to the key findings of the paper: while listing the extent of moorland burning found in the scientific paper, comments in the press releases are primarily made regarding the "damaging" effect of fire. This is perhaps of little surprise given that the RSPB is in frequent conflict with the U.K. land-management community over a range of issues, including the ethics of driven grouse shooting and the persecution of raptors (Whitfield et al. 2003). Individuals closely associated with the RSPB have made unambiguous calls for burning to be banned (Avery 2014). We, therefore, suspect that much of the contextualisation in recent fire-related studies stems less from evidence of the environmental effects of managed burning and more from attitudes towards the forms of land-ownership and other management practices associated with burning in the U.K. There are undoubtedly systemic issues associated with some aspects of grouse moor management in the U.K. (e.g. Whitfield et al. 2003), and it has been previously argued that fire management practices that are focused solely on production of grouse, and justified on the basis of tradition alone, are unlikely to provide ecologically-resilient, multi-functional upland landscapes (Davies et al. 2008). Whilst the cultural history of fire use can be an important consideration in determining fire management policy (Mistry et al. 2016; Pyne 2016), it should certainly not be used as justification for the continuation of unsustainable practices. Here the picture becomes more complex as perceptions of sustainability depend upon the ecosystem services a particular group or individual prioritises and there are inevitable trade-offs between different services (Reed et al. 2013).

There are a wide range of views on issues regarding the socioeconomics and ethics of private estate ownership and driven grouse shooting in the U.K., both within the research community at large and amongst the authors here. Effective communication and understanding between different groups currently seems to be minimal. Reports that some land managers believe they have access to "special" knowledge regarding moorlands that others cannot comprehend (Dinnie et al. 2015) are thus concerning. However so too is the fact that conservationists often seem unable to make objective interpretations of individual ecological management practices, such as prescribed burning, independent of the wider moorland management context. There can often be a complex relationship with managed fire even within a single organisation. In our own research we have experienced managers in one region not prepared to contemplate even a single research burn on a bog, whilst those from the same organisation, but based an hour up the road, have actively sought us out to trial burning on similar sites. Furthermore, RSPB research has shown the value of prescribed fire as a tool to promote woodland expansion at forest-moorland edges and to manage Capercaillie (*Tetrao urogallus* Linnaeus, 1758) habitat (Hancock et al. 2011). By campaigning so strongly on the presumed negative effects of burning on peatland ecosystems the RSPB thus risk undermining the ability of their own managers to use fire as an ecological tool. Organisations like the RSPB, which have to balance ecological campaigning and management roles, often face the challenge of aligning local management needs with dominant narratives or 'party lines'. It would be preferable if ecological knowledge were allowed to determine attitudes rather than vice versa. We recognise that individuals are at liberty to form their own opinions on subjective issues like the aesthetics of certain landscapes or the ethics of hunting, but as environmental scientists we have a duty to ensure we do not conflate opinion with evidence and to acknowledge where we lack knowledge. The problem with the tone of the current debate in the media was neatly summarised by Thorp (2015): "*I was struck by what a waste of time these exchanges were, as no-one is going to trot out anything but their safest party line on these occasions. In my view, this type of exchange only serves to feed sensation, deepen the trenches and sell publications/increase ratings*."

Assessing how science communication affects perceptions

To determine how non-specialists' perceptions of fire are influenced by differences in reporting in academic and public media, we distributed one of the following to each of six separate groups of six to seven senior undergraduate and graduate students of restoration ecology at The Ohio State University (USA): the results or discussion sections of Douglas et al. (2015); an associated RSPB press release (RSPB 2015a); and subsequent media coverage (Doward 2015; The Ecologist 2015). The material extracted from Douglas et al. (2015) was modified to remove the citations so it was not immediately apparent what kind of publication each reading came from. Each group of students was asked to come to a consensus about what they perceived to be the two key research findings of their reading. Responses from those reading the results section correctly concluded the key findings were that burning was increasing and that it was strongly associated with protected areas. This was in contrast to responses from those reading the discussion, press release and newspaper articles, who concluded that key findings were that burning took place in protected areas and that burning was damaging to peatland ecosystems. The difference in the groups' perceptions demonstrate Douglas et al.'s own discussion of their findings, and the associated outreach and media coverage gives the impression that the paper focused on the environmental and ecological effects of burning. In reality, the work described the spatial distribution of burning and short-term temporal trends in fire; the results of which have been questioned (Davies et al. 2016).

If we are to debate the use of fire as a management tool, it is essential that authors ensure that the publicity associated with their findings accurately reflects the content of their research as well as the uncertainty associated with ongoing research questions. At the same time, it is also essential that journalists reporting on this clearly contentious topic do not just rely on the content of press releases from campaigning organisations but verify facts by reading the actual paper and consulting with an independent academic expert not involved in the study. Journalists reporting on scientific findings need to decide whether their duty is to report science or further their own or others' agendas. Journalists should preferably adopt a neutral tone and make a clear distinction between research reporting and opinion pieces.

Priorities for future research

Fire as a management tool is carried out at the landscape scale and induces ecological processes that span from minutes to decades following the burn. Most research relies on small plots of 1-10's of meters and might, at best, extend for a couple of years following the fire. The only U.K. site where long term evidence is available on peatland burning is Moor House in the Pennines. Even these experimental plots are not at a landscape scale (900m^2, Marrs et al. 1986) and the fire rotations are unlikely to be applied in real situations since recommendations stipulate longer rotations in peatlands (see Muirburn Code; Scottish Government 2011). Alternatives are to take chronosequence or catchment comparison type approaches as these are often the only way to approach questions regarding longer-term fire effects in the absence of replicated experiments. Unfortunately, such studies are replete with assumptions, for instance that catchments would have similar physical, chemical and hydrological characteristics in the absence of burning. They can also have difficulty in ascribing causality, particularly where past and present management regimes cannot be adequately documented. For instance, past wildfire history may also be a significant component of the fire regime. Developing an integrated, holistic understanding of the effect of variation in fire regimes on peatland ecosystems is likely to require a combination of study types and a multidisciplinary approach including land-managers, ecologists, hydrologists, fire scientists, sociologists and economists. Co-ordinated, distributed experiments (Fraser et al. 2013) across different peatland ecosystem perhaps also hold promise if our aim is to try and develop more generalisable knowledge regarding fire effects on peatlands. Much knowledge also exists elsewhere in

North-West Europe where many peatland ecosystems have similar vegetation and management histories (e.g. Kaland 1986). Limited funding for peatland research means that research groups often seem to be in competition with each other. This has had an effect on research quality as groups with widely differing backgrounds and expertise (e.g. hydrologists, plant ecologists, carbon scientists, fire scientists) try to be all things to all people, leading to inevitable gaps in knowledge and understanding that subsequently surface in methodologies and interpretations. A good example of this can be seen in the recent exchange between Douglas et al. (2016) and Davies et al. (2016). Here, the reasons for the misinterpretation of the results of MODIS fire detections by Douglas et al. (2015) was revealed in their subsequent response (Douglas et al. 2016), as it became apparent they had confused the concepts of "burn area" (i.e. the total area burnt by a fire) with "fire front area" (the area of actual flaming combustion at any one point in time). We agree with the proposition in Brown et al. (2015a) that more integrated working between researchers is needed, and that catchment scale manipulations and networks of long-term experimental burn sites are urgently required. Working in partnership with land managers, fire professionals and other non-academic stakeholders to co-produce knowledge is another approach to extend the spatial and temporal range of data collection, incorporate local knowledge and build trust (Phillipson et al. 2012; Reed et al. 2014)

Recent reviews (e.g. Glaves et al. 2013) have drawn attention to the very significant knowledge gaps that remain with regards to the effects of fire on peatland ecosystems. We do not dispute the fact that fire causes a range of ecological and environmental changes - some of which are less welcome than others with a mixture of costs and benefits. There is, however, very considerable uncertainty and knowledge is missing in several key areas. On-going research in the U.K. is certainly not being helped by the fact that several studies seem to be operating in a vacuum where understanding from wildland fire science and peatland ecology more generally is missing and leading to methodological and interpretational errors. In particular here, is the argument from wildland fire scientists in the USA (e.g. Busenberg 2004; Miller et al. 2009) and Mediterranean (e.g. San Miguel-Ayannz et al. 2013; Tabara et al. 2003) that fire exclusion (or the "over-suppression paradigm") allows fuels to accumulate and ultimately increases fire intensity and burn severity. This hypothesis has not yet been tested in the U.K. context; indeed even a baseline assessment of fuel load and continuity would be a welcome start.

Whether or not current land-management priorities, burning regimes and other practices are ecologically sustainable, or morally-justifiable, in the context of social and environmental change are questions that still require significant further study and debate. There is currently little scientific consensus either way with often contradictory results on the effects of fire on DOC concentrations on moorland water (Holden et al. 2012) and gaseous carbon emissions from peat soils where, again, the majority of the evidence is from Moor House (e.g. Ward 2007). Some results, such as the finding that burning benefits at least some *Sphagnum* species (Lee et al. 2013; Hamilton 2000) directly challenge current perceptions and require further study. Brown et al. (2015a) were right to point out that too much of our knowledge comes from a small number of sites and that experimental treatments may not be representative of the variety of management practices on the ground. Larger catchment scale comparisons of the type completed in Brown et al. (2014) should be welcomed, though they also have their issues as they make the implicit assumption of similar long-term historical land-use and similar underlying abiotic conditions (something the results of Rosenburgh et al. 2013 suggest is unlikely).

We argue here that the following important factoids are not verified. They require further study and should not be perpetuated in discussions until they are formally addressed:

- That regular burning increases *Calluna* dominance. Areas associated with burning tend to have greater *Calluna* cover but managers do not distribute their effort randomly across landscapes and it's unclear if burning is the result or cause of increased *Calluna* cover. Time-scale is also important. Indeed, not burning vegetation with a substantive *Calluna* component will increase its dominance at least over a 90-year period, a time range close to the natural historic fire-return interval of 120-200 years (Lee et al. 2013).
- That fire kills or significantly damages *Sphagnum*. We need to quantify species responses to fire and to understand the importance of variation in burn severities and frequencies. *Sphagnum* species display micro-habitat differences (hummock, hollow, pool, and lawn) and it is likely that micro-habitats will respond to burning differently given their distinct topography and moisture regimes. We also need to know whether burning limits *Sphagnum* recovery during peatland restoration and if so, under what fire regimes?
- That peatlands are particularly sensitive sites with regards to fire. Northern peatlands elsewhere in the world, notably within boreal regions, can show remarkable ecohydrological resilience to burning (Thompson and Waddington 2013; Thompson et al. 2014). Interactions with drainage can however induce remarkable changes in this regard (Turetsky et al. 2011). Such findings have received little attention in the context of U.K. peatland management.

- That managed burning helps protect against future wildfires, minimising fire likelihood and burn severity. How does managed burning affect landscape-scale patterns in flammability; does it reduce the frequency or burn severity of wildfires? How many wildfires actually result from managed burning? In other words, how do wildfire and managed fire regimes interact?
- That fire alone can contribute to peatland degradation. At what frequencies or severities is this true, if at all? How can we separate the confounded effects of drainage, grazing, acidification and nutrient deposition? Unlike wildfires, managed burns appear to rarely leave areas of peat exposed but might this vary according to fire frequency? Over what spatial and temporal scales should degradation be defined?

Conclusion

Fire is a valued and integral component of the ecosystem manager's tool kit capable of being used as well as abused in a multiplicity of different ways. Throughout Europe managers, ecologists and conservationists value prescribed burning as a tool to protect and restore globally-rare heathland and moorland ecosystems and there is a growing body of scientific literature to inform best practice. Much of this knowledge comes from research in the U.K. and it is ironic that whilst the debate here has shifted strongly against the use of fire, scientists in other countries are using this evidence to promote the reintroduction of burning. Further scientific evidence is urgently needed on the benefits and costs of differing fire regimes for peatland and moorland ecosystem services. Such assessments need to focus on the landscape scale and on elucidating trends over the entire fire rotation rather than just looking at the short-term outcomes of single burns which are a pulse disturbance with obvious negative outcomes for particular metrics. Until integrated evidence is available, all scientists should be concerned when potentially interesting and informative research is used as a forum to propagate what amounts to hearsay or to promote political agendas. The use of press releases to publicise a particular point of view when the actual scientific evidence from a study is incomplete or unrelated should be discouraged.

In the absence of sound evidence and consensus, it is vital that managers and scientists adopt an "Adaptive" approach to decision making (Holling 1978). Core principles of Adaptive Management include the need to monitor and learn from management actions, to keep an open mind until the evidence is settled and consensus reached and to involve all stakeholders and viewpoints in decision making. Managing for a single ecosystem service, be that traditional burning practices game for production or banning burning to try and reduce the colour of drinking water, is unlikely to meet with success if the wider impacts of management regimes are not considered (Reed et al. 2013). It is vitally important for both scientists and journalists to ensure objective outreach and reporting on this on-going and contentious debate as trust between stakeholders risks reaching rock-bottom.

Restoring resilient peatland ecosystems that protect existing carbon stocks and function as a carbon sink is a priority for the U.K. and we welcome initiatives such as Scottish Natural Heritage's Peatland Plan (SNH 2015). What is clear to us is that approaches to science and science communication that ignore complexity, seek to propagate agendas and alienate stakeholder groups on either side of the debate are not doing anyone a favour in the long-term. A narrow 'bounded rationality' that bases decisions on evidence from a selective perspective instead of a holistic one is liable to lead to policy failure, as Busenberg (2004) argues was the case for US fire policy. Prescribed burning is a potential tool for peatland management and restoration along with other techniques such as grazing, cutting or ditch-blocking. Like all ecological tools, fire can be used well or poorly and will not be suitable in all situations. We are certainly not arguing that across the U.K. the status-quo necessarily represents best-practice or that it will deliver resilient peatland ecosystems. However, if we want to retain moorlands and peatlands as part of a diversity of upland landscape structures fire will need to be part of their management. Though managers seem to mostly follow current recommended guidelines on burning (Allen et al. 2015), traditional approaches to managed burning have room for improvement but do deliver significant conservation benefits (Thompson et al. 1995, Davies et al. 2008). Our objective should be to use fire as one tool in management that aims to produce structurally diverse upland landscapes that protect a range of ecosystem functions. The conversation needs to move away from unhelpful hyperbole about banning part of the ecosystem manager's toolkit and focus on learning how to use it well. This could include better technical training in fire use, certification for fire users, explicit integration of knowledge regarding relationships between fire behaviour and fire effects and an increased emphasis on monitoring and compliance. Such changes would be a first step to facilitating more precise and targeted fire use that maximises benefits, minimises detrimental environmental impacts and builds trust between stakeholders.

Competing interests

We have no competing interests. Some of the authors currently or have, in the past, worked for/with or received funding from the Game and Wildlife Conservation Trust, Scottish Natural Heritage, Natural England, and the Royal Society for the Protection of Birds.

Authors' contributions

The authors contributed equally to this publication

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References

Alday, J. G., E. S. Cox, R. J. Pakeman, M. P. K. Harris, M. G. Le Duc, and R. H. Marrs. 2013. Effectiveness of Calluna-heathland restoration methods after invasive plant control. Ecological Engineering 54:218-226.

Allen, K. A., M. P. K. Harris, and R. H. Marrs. 2013. Matrix modelling of prescribed burning in Calluna vulgaris-dominated moorland: short burning rotations minimize carbon loss at increased wildfire frequencies. Journal of Applied Ecology 50:614-624.

Allen, K. A., P. Denelle, F. M. Sánchez Ruiz, V. M. Santana, and R. H. Marrs. 2016. Prescribed moorland burning meets good practice guidelines: a monitoring case study using aerial photography in the Peak District, UK. Ecological Indicators, 62, 76-85.

Allen, S. E. 1964. Chemical aspects of heather burning. Journal of Applied Ecology 1:347-367.

Altangerel, K., and C. A. Kull. 2013. The prescribed burning debate in Australia: Conflicts and compatibilities. Journal of Environmental Planning and Management 56:103-120.

Amos I. 2014. Cut heather burning for sake of the environment. The Scotsman. URL: http://www.scotsman.com/news/environment/cut-heather-burning-for-sake-of-the-environment-1-3558555#axzz3ntH0zyFj [Accessed 01/Nov/2015].

Armstrong, A., J. Holden, K. Luxton, and J. N. Quinton. 2012. Multi-scale relationship between peatland vegetation type and dissolved organic carbon concentration. Ecological Engineering 47:182-188.

Ascoli, D., R. Beghin, R. Ceccato, A. Gorlier, G. Lombardi, M. Lonati, R. Marzano, G. Bovio, and A. Cavallero. 2009. Developing an Adaptive Management approach to prescribed burning: a long-term heathland conservation experiment in north-west Italy. International Journal of Wildland Fire 18:727-735.

Avery M. (2014) Burn, maybe burn (aka Wuthering Moors 40) URL: http://markavery.info/2014/03/07/burn-burn/ [Accessed 01/Nov/2015].

Barnett B. 2014. Burning debate reignited. Yorkshire Post. URL: http://www.yorkshirepost.co.uk/mobile/news/rural/farming/burning-debate-reignited-1-6877466 [Accessed 01/Nov/2015].

Barnett B. 2015. Moorland burning ‘threatens protected landscape’. Yorkshire Post. URL: http://www.yorkshirepost.co.uk/news/rural/farming/moorland-burning-threatens-protected-landscape-1-7368494 [Accessed 01/Nov/2015].

Battle, J., and S. W. Golladay. 2003. Prescribed fire's impact on water quality of depressional wetlands in southwestern Georgia. American Midland Naturalist 150:15-25.

Belcher C. M. 2013. Fire Phenomena and the Earth System: An Interdisciplinary Guide to Fire Science, Wiley, London.

Benscoter, B. W., and D. H. Vitt. 2008. Spatial Patterns and Temporal Trajectories of the Bog Ground Layer Along a Post-Fire Chronosequence. Ecosystems 11:1054-1064.

Bergner, B., J. Johnstone, and K. K. Treseder. 2004. Experimental warming and burn severity alter soil CO2 flux and soil functional groups in a recently burned boreal forest Global Change Biology 10:1996-2004.

Blundell A. and J. Holden. 2015. Using palaeoecology to support blanket peatland management, Ecological Indicators, 49, 110-120.

Bowman, D. M. J. S., J. K. Balch, P. Artaxo, W. J. Bond, J. M. Carlson, M. A. Cochrane, C. M. D'Antonio, R. S. DeFries, J. C. Doyle, S. P. Harrison, F. H. Johnston, J. E. Keeley, M. A. Krawchuk, C. A. Kull, J. B. Marston, M. A. Moritz, I. C. Prentice, C. I. Roos, A. C. Scott, T. W. Swetnam, G. R. van der Werf, and S. J. Pyne. 2009. Fire in the Earth System. Science 324:481-484.

Brown P. 2014. ‘Amazon of UK’ being destroyed for grouse shooting. Climate News Network. URL: http://climatenewsnetwork.net/amazon-of-uk-being-destroyed-for-grouse-shooting [Accessed 01/Nov/2015].

Brown, L. E., J. Holden, S. M. Palmer, K. Johnston, S. J. Ramchunder, and R. Grayson. 2015a. Effects of fire on the hydrology, biogeochemistry, and ecology of peatland river systems. Freshwater Science, 34, 1406-1425.

Brown, L.E., Palmer, S.M., Johnston, K., Holden, J., 2015b. Vegetation management with fire modifies peatland soil thermal regime. Journal of Environmental Management 154:166-176.

Brown, L. E., J. Holden, and Palmer, S. M. 2014. Effects of moorland burning on the ecohydrology of river basins. Key findings from the EMBER project. University of Leeds. Available from:

http://www.wateratleeds.org/fileadmin/documents/water_at_leeds/Ember_report.pdf [Accessed 17th February 2016].

Buchanan, G. M., M. C. Grant, R. A. Sanderson, and J. W. Pearce-Higgins. 2006. The contribution of invertebrate taxa to moorland bird diets and the potential implications of land-use management. Ibis 148:615-628.

Busenberg G. 2004. Wildfire management in the United States: the evolution of a policy failure. Review of Policy Research 21:145-156.

Cawson, J., G. Sheridan, H. Smith, and P. Lane. 2012. Surface runoff and erosion after prescribed burning and the effect of different fire regimes in forests and shrublands: a review. International Journal of Wildland Fire 21:857-872.

Clay, G.D., Worrall, F., Fraser, E.D.G., 2009. Effects of managed burning upon dissolved organic carbon (DOC) in soil water and runoff water following a managed burn of a UK blanket bog. Journal of Hydrology 367, 41-51.

Clay, G.D., Worrall, F., Rose, R., 2010a. Carbon budgets of an upland blanket bog managed by prescribed fire. Journal of Geophysical Research - Biogeosciences, 115: G04037.

Clay, G.D., Worrall, F., Fraser, E.D.G., 2010b. Compositional changes in soil water and runoff water following managed burning on a UK upland blanket bog. Journal of Hydrology, 380(1-2): 135-145.

Clay, G. D., F. Worrall, N. J. Aebischer. 2012. Does prescribed burning on peat soils influence DOC concentrations in soil and runoff waters? Results from a 10 year chronosequence. Journal of Hydrology 448: 139-148.

Clay, G.D., Worrall, F., Aebischer, N.J., 2015. Carbon stocks and carbon fluxes from a 10-year prescribed burning chronosequence on a UK blanket peat. Soil Use and Management, 31(1): 39-51.

Clutterbuck, B., Yallop, A.R., 2010. Land management as a factor controlling dissolved organic carbon release from upland peat soils 2: Changes in DOC productivity over four decades. Science of the Total Environment 408, 6179-6191.

Clymo, R. S., and J. G. Duckett. 1986. Regeneration of Sphagnum. New Phytologist 102:589-614.

Davies C. 2015. Shooting industry must stop putting strain on countryside, says RSPB chief. The Guardian. URL: http://www.theguardian.com/environment/2015/jul/31/shooting-industry-rspb-strain-countryside-game-birds-intensive-management [Accessed 01/Nov/2015].

Davies G. M., A. Gray, R. Domenech Jardi, and P. Johnson. 2014. Variation in peatland wildfire severity – implications for ecosystem carbon dynamics. In: Viegas D.X. (Ed.) Advances in Forest Fire Research. Imprensa da Universidade de Coimbra, Coimbra, Portugal.

Davies G. M., C. R. Stoof, N. Kettridge, and A. Gray. 2016. Comment on: Vegetation burning for game management in the UK uplands is increasing and overlaps spatially with soil carbon and protected areas. Biological Conservation.

Davies G.M. 2013. Understanding fire regimes and fires' ecological effects. In: Belcher C.M. (Ed.) Fire Phenomena and the Earth System: An Interdisciplinary Guide to Fire Science. Wiley: London.

Davies, G. M., A. A. Smith, A. J. MacDonald, J. D. Bakker, and C. J. Legg. 2010. Fire intensity, fire severity and ecosystem response in heathlands: factors affecting the regeneration of *Calluna vulgaris*. Journal of Applied Ecology 47:356-365.

Davies, G. M., A. Gray, G. Rein, and C. J. Legg. 2013. Peat consumption and carbon loss due to smouldering wildfire in a temperate peatland. Forest Ecology and Management 308:169-177.

Davies, G. M., and C. J. Legg. 2008. The effect of traditional management burning on lichen diversity. Applied Vegetation Science 11:529-538.

Davies, G. M., R. Domènech, A. Gray and P. C. D. Johnson. 2016. Vegetation structure and fire weather influence variation in burn severity and fuel consumption during peatland wildfires. Biogeosciences, 13, 389-398.

Davies, G. M., A. Gray, A. Hamilton, and C. J. Legg. 2008. The future of fire management in the British uplands. International Journal of Biodiversity Science & Management 4:127-147.

Dinnie, E., Fischer A., and Huband S. 2015. Discursive claims to knowledge: The challenge of delivering public policy objectives through new environmental governance arrangements. Journal of Rural Studies 37: 1-9.

Dodgshon, R. A., and G. A. Olsson. 2006. Heather moorland in the Scottish Highlands: the history of a cultural landscape, 1600-1880. Journal of Historical Geography 32:21-37.

Douglas, D. J., G. M. Buchanan, P. Thompson, A. Amar, D. A. Fielding, S. M. Redpath, and J. D. Wilson. 2015. Vegetation burning for game management in the UK uplands is increasing and overlaps spatially with soil carbon and protected areas. Biological Conservation 191:243-250.

Douglas, D. J., G. M. Buchanan, P. Thompson, T. Smith, T. Cole, A. Amar, D. A. Fielding, S. M. Redpath, and J. D. Wilson. 2016. Reply to comment on: Vegetation burning for game management in the UK uplands is increasing and overlaps spatially with soil carbon and protected areas. Biological Conservation.

Doward. 2015. Peatlands burn as gamekeepers create landscape fit for grouse-shooting, URL: http://www.theguardian.com/environment/2015/jul/05/peat-bogs-burning-grouse-shooting [Accessed 05/Nov/2015].

Ekström, S. M., Kritzberg, E. S., D. B. Kleja, N. Larsson, P. A. Nilsson, W. Graneli, and B. Bergkvist. 2011. Effect of Acid Deposition on Quantity and Quality of Dissolved Organic Matter in Soil–Water. Environ. Sci. Technol. 45: 4733–4739.

Elliott, R. J. 1953. The effects of burning on hether moors of the South Pennines. PhD Thesis. University of Sheffield, Sheffield.

Fahnestock, J., 1986. Accommodating Science: The Rhetorical Life of Scientific Facts. Written Communication, 3(3): 275-296.

Fernandes, P. M., G. M. Davies, D. Ascoli, C. Fernandez, F. Moreira, E. Rigolot, C. R. Stoof, J. A. Vega, and D. Molina. 2013. Prescribed burning in southern Europe: developing fire management in a dynamic landscape. Frontiers in Ecology and the Environment 11:E4-E14.

Garnett, M. H. 1998. Carbon storage in Pennine moorland and response to change. PhD Thesis. University of Newcastle-Upon-Tyne, Newcastle-Upon-Tyne.

Garnett, M. H., P. Ineson, and A. C. Stevenson. 2000. Effects of burning and grazing on carbon sequestration in a Pennine blanket bog, UK. The Holocene 10:729-736.

Glaves, D., M. Morecroft, C. Fitzgibbon, M. Owen, S. Phillips, and P. Leppitt, P. 2013. The Effects of Managed Burning on Upland Peatland Biodiversity, Carbon and Water. Natural England Evidence Review NEER004, Peterborough, UK.

Grau R., G.M. Davies., S. Waldron, A. Gray, and M. Bruce. 2014. Fuel and climate controls on peatland fire severity. In: Viegas D.X. (Ed.) Advances in Forest Fire Research. Imprensa da Universidade de Coimbra.

Gunnarsson, U., N. Malmer, and H. Rydin. 2002. Dynamics or constancy in Sphagnum dominated mire ecosystems? A 40-year study. Ecography 25: 685-704.

Haddaway N. R. and H. R. Bayliss. 2015. Shades of grey: two forms of grey literature important for reviews in conservation. Biological Conservation 191:827-829.

Haddaway N.R. and J. T. A. Verhoeven. 2015. Poor methodological detail precludes experimental repeatability and hampers synthesis in ecology. Ecology and Evolution 5:4451-4454.

Hamilton, A. 2001. The characteristics and effects of management fire on blanket bog vegetation in north west Scotland. University of Edinburgh, Scotland. http://hdl.handle.net/1842/7120, http://hdl.handle.net/1842/7120.

Hancock, M. H., A. Amphlett, R. Proctor, D. Dugan, J. Willi, P. Harvey, and R. W. Summers. 2011. Burning and mowing as habitat management for capercaillie *Tetrao urogallus*: An experimental test. Forest Ecology and Management 262:509-521.

Harris, M. P., K. A. Allen, H. A. McAllister, G. Eyre, M. G. Le Duc, and R. H. Marrs. 2011. Factors affecting moorland plant communities and component species in relation to prescribed burning. Journal of Applied Ecology 48:1411-1421.

Harrison J. 2015. Moorland report criticises heather burning. The Herald. URL: http://www.heraldscotland.com/news/13476809.Moorland_report_criticises_heather_burning [Accessed 01/Nov/2015].

Hart T. 2014. Burn moor, or less? Geographical. URL: http://geographical.co.uk/nature/climate/item/357-burn-moor-or-less [Accessed 01/Nov/2015].

Hester, A. J., and C. Sydes. 1992. Changes in burning of Scottish heather moorland since the 1940s from aerial photographs. Biological Conservation: 60, 25-30.

Holden J., P. J. Chapman, S.M. Palmer, P. Kay, R. Grayson. 2012. The impacts of prescribed moorland burning on water colour and dissolved organic carbon: A critical synthesis. Journal of Environmental Management 101: 92-103.

Holden, J., L. Shotbolt, A. Bonn, T. P. Burt, P. J. Chapman, A. J. Dougill, E. D. G. Fraser, K. Hubacek, B. Irvine, M. J. Kirkby, M. S. Reed, C. Prell, S. Stagl, L. C. Stringer, A. Turner, and F. Worrall. 2007. Environmental change in moorland landscapes. Earth-Science Reviews 82:75-100.

Holling C. S. 1978. Adaptive environmental assessment and management. New York: John Wiley and Sons.

Hornman, M., and R. Haveman. 2001. Flora and fauna op militaire oefenterreinen. De Levende Natuur 102:173-176.

ITV. 2015. Protest against grouse shooting on Ilkley Moor. ITV. URL: http://www.itv.com/news/calendar/2015-10-03/protest-against-grouse-shooting-on-ilkley-moor [Accessed 01/Nov/2015].

Jaatinen, K., C. Knief, P. F. Dunfield, K. Yrjala, and H. Fritze. 2004. Methanotrophic bacteria in boreal forest soil after fire. FEMS Microbiology Ecology 50:195-202.

Jaffe, R., Y. Ding, J. Niggemann, A. V. Vahatalo, A. Stubbins, R. G. M. Spencer, J. Campbell, and T. Dittmar. 2013. Global Charcoal Mobilization from Soils via Dissolution and Riverine Transport to the Oceans. Science 340:345-347.

JNCC [Joint Nature Conservation Commission]. 2009. Common Standards Monitoring Guidance for Upland habitats. London, JNCC. URL: http://jncc.defra.gov.uk/page-2237 [Accessed 01/Nov/2015].

Kritzberg, E. S., and S. M. Ekstrom. 2012. Increasing iron concentrations in surface waters - a factor behind brownification? Biogeosciences 9:1465-1478.

Kuhry, P. 1994. The role of fire in the development of Sphagnum-dominated peatlands in western boreal Canada. Journal of Ecology 82:899-910.

Lee, H., J. G. Alday, R. J. Rose, J. O'Reilly, and R. H. Marrs. 2013. Long-term effects of rotational prescribed burning and low-intensity sheep grazing on blanket-bog plant communities. Journal of Applied Ecology 50:625-635.

Legg C. J., E. Maltby, and M. C. F. Proctor. 1992. The ecology of severe moorland fire on the North York Moors: seed distribution and seedling establishment of *Calluna vulgaris*. Journal of Applied. Ecology. 80: 737–752.

Legg, C. J., G. M. Davies, K. Kitchen, and P. Marno. 2007. Developing a Fire Danger Rating System for the UK: FireBeaters Phase I final report. Report to the Scottish Wildfire Forum.

Limpens, J., F. Berendse, C. Blodau, J. G. Canadell, C. Freeman, J. Holden, N. Roulet, H. Rydin, and G. Schaepman-Strub. 2008. Peatlands and the carbon cycle: from local processes to global implications – a synthesis. Biogeosciences 5:1475-1491.

Lindsay R. 2010. Peat bogs and carbon: a critical synthesis to inform policy development in oceanic peat bog conservation and restoration in the context of climate change. Unpublished report. URL: https://rspb.org.uk/Images/Peatbogs_and_carbon_tcm9-255200.pdf [Accessed 03/Nov/2015].

Lindsay, R. A., D. J. Charman, F. Everingham, R. M. O'Reilly, M. A. Palmer, T. A. Rowell and D. A. Stroud 1988. The Flow Country - The peatlands of Caithness and Sutherland. JNCC, Peterborough.

MacDonald, A. J., A. H. Kirkpatrick, A. J. Hester and C. Sydes. 1995. Regeneration by natural layering of heather (*Calluna vulgaris*): frequency and characteristics in upland Britain. Journal of Applied Ecology, 32, 85-99.

Maltby, E., C. J. Legg, and M. C. F. Proctor. 1990. The ecology of severe moorland fire on the North York Moors: effects of the 1976 fires, and subsequent surface and vegetation development. Journal of Ecology 78:490-518.

Manighetti E. 2015. Why We Should Rewild The British Uplands. The Huffington Post. URL: http://www.huffingtonpost.co.uk/elena-manighetti/why-we-should-rewild-the-_b_7921768.html [Accessed 01/Nov/2015].

Marrs, R.H., M. Rawes, J. S. Robinson, and S. D. Poppitt. 1986. Long- term studies of vegetation change at Moor House NNR: guide to recording methods and database. Merlewood Research & Development Paper 109. ITE, Grange-over-Sands.

Mistry, J., B. Bilbao, A. Berardi (2016). Community owned solutions for fire management in tropical ecosystems: case studies from Indigenous communities of South America. This volume.

Monbiot G. 2016. Meet the conservationists who believe that burning is good for wildlife. The Guardian. Available from: http://www.theguardian.com/environment/georgemonbiot/2016/jan/14/swaling-is-causing-an-environmental-disaster-on-britains-moors [Accessed 11th February 2016].

Moody, C.S., Worrall, F., Evans, C.D., Jones, T.G., 2013. The rate of loss of dissolved organic carbon (DOC) through a catchment. Journal of Hydrology 492, 139-150.

Neary, D. G., C. C. Klopatek, L. F. DeBano, and P. F. Ffolliott. 1999. Fire effects on belowground sustainability: A review and synthesis. Forest Ecology and Management 122:51-71.

Neary, D. G., K. C. Ryan and L. F. DeBano. 2005. Wildland fire in ecosystems: effects of fire on soils and water. General Technical Report RMRS-GTR-42-vol.4. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT.

Pearce F. 2006. Grouse-shooting popularity boosts global warming. New Scientist. URL: https://www.newscientist.com/article/mg19125644-000-grouse-shooting-popularity-boosts-global-warming [Accessed 01/Nov/2015].

Phoenix, G. K., B. A. Emmett, A. J. Britton, S. J. M. Caporn, N. B. Dise, R. Helliwell, L. Jones, J. R. Leake, I. D. Leith, L. J. Sheppard, A. Sowerby, M. G. Pilkington, E. C. Rowe, M. R. Ashmore, and S. A. Power. 2012. Impacts of atmospheric nitrogen deposition: responses of multiple plant and soil parameters across contrasting ecosystems in long-term field experiments. Global Change Biology 18:1197-1215.

Pitkänen, A., J. Turunen, and K. Tolonen. 1999. The role of fire in the carbon dynamics of a mire, eastern Finland. The Holocene 9: 453–462.

Pyne, S.J. 2016. Fire in the mind: changing understandings of fire in Western civilization. This volume.

Pyne, S. J., P. L. Andrews, and R. D. Laven. 1996. Introduction to wildland fire. John Wiley and Sons.

Ramchunder, S. J., L. E. Brown, and J. Holden. 2013. Rotational vegetation burning effects on peatland stream ecosystems. Journal of Applied Ecology 50: 636–648.

Reed M. S., K. Hubacek, A. Bonn, T. P. Burt, J. Holden, L. C. Stringer, N. Beharry-Borg, S. Buckmaster, D. Chapman, P. Chapman, G. D. Clay, S. J. Cornell, A. Dougill, A. C. Evely, E. D. G. Fraser, N. Jin, B. J. Irvine, M. J. Kirkby, W. E. Kunin, C. Prell, C. H. Quinn, B. Slee, S. Stagl, M. Termansen, S. Thorp and F. Worrall. 2013. Anticipating and managing future trade-offs and complementarities between ecosystem services. Ecology and Society 18:5. DOI: 10.5751/ES-04924-180105

Robertson, R. A., and G. E. Davies. 1965. Quantities of plant nutrients in heather ecosystems. Journal of Applied Ecology 2:211-219.

Romme W. 1980. Fire History Terminology: Report of the Ad Hoc Committee. In: Stokes M.A. & Dieterich J.H. (eds.) Proceedings of the fire history workshop. Oct 20-24, 1980; Tucson, Arizona. General

Technical Report RM-GTR-81. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Rosenburgh A., J. G. Alday, M. P. K. Harris, K. A. Allen, L. Connor, S. J. Blackbird, G. Eyre, and R. H. Marrs. 2013. Changes in peat chemical properties during post-fire succession on blanket bog moorland, Geoderma 211: 98-106.

Ross D. 2014. Burning of heather 'damaging peatlands and rivers'. The Herald. URL: http://www.heraldscotland.com/news/13182619.Burning_of_heather__damaging_peatlands_and_rivers_ [Accessed 01/Nov/2015].

Rothwell, J.J., Evans, M.G., Liddaman, L.C., Allott, T.E.H., 2007. The role of wildfire and gully erosion in particulate Pb export from contaminated peatland catchments in the southern Pennines, U.K. Geomorphology, 88(3–4): 276-284.

RSPB 2015a. RSPB-led study reveals extent of upland burning across Britain, URL: http://www.rspb.org.uk/media/releases/details.aspx?id=403979 [Accessed 05/Nov/2015]

RSPB 2015b.RSPB chief executive challenges shooting industry to ‘take responsibility for its impacts

http://www.rspb.org.uk/media/releases/404769-rspb-chief-executive-challenges-shooting-industry-to-take-responsibility-for-its-impacts- [Accessed 05/Nov/2015]

RSPB 2015c. Our uplands are becoming a burning issue

http://www.rspb.org.uk/news/404053-our-uplands-are-becoming-a-burning-issue [Accessed 05/Nov/2015]

Ryan, K. C., E. E. Knapp, and J. M. Varner. 2013. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. Frontiers in Ecology and the Environment 11:e15-e24.

San-Miguel-Ayanz J, Moreno JM, Camia A. 2013. Analysis of large fires in European Mediterranean landscapes: lessons learned and perspectives. Forest Ecology & Management 294:11–22.

Santín, C., S.H. Doerr, E. Kane, C. Masiello, M. Ohlson, C. Preston, A. de la Rosa, and T. Dittmar. 2016. Towards a global assessment of pyrogenic carbon from vegetation fires. Global Change Biology, 22:76-91.

Scanlon, D. and T. Moore. 2000. Carbon dioxide production from peatland soil profiles: the influence of temperature, oxic/anoxic conditions and substrate. Soil Science, 165, 153-160.

Scottish Government. 2011. The Muirburn Code. Edinburgh, The Scottish Government. URL: http://www.gov.scot/Publications/2011/08/09125203/0 [Accessed 01/Nov/2015].

Shaw, S.C., B. D. Wheeler, P. Kirby, P. Phillipson, and R. Edmunds. 1996. Literature Review of the Historical Effects of Burning and Grazing of Blanket Bog and Upland Wet Heath. English Nature Research Reports, Number 172. English Nature and Countryside Council for England and Wales, Peterborough.

Shuttleworth, E.L., Evans, M.G., Hutchinson, S.M., Rothwell, J.J., 2015. Peatland restoration: controls on sediment production and reductions in carbon and pollutant export. Earth Surface Processes and Landforms 40, 459-472.

Simmons, I. G. 1990. The mid-Holocene ecological history of the moorlands of England and Wales and its relevance for conservation. Environmental Conservation 17:61-69.

Simmons, I. G. 2003. The Moorlands of England and Wales an Environmental History, 8000 BC - AD 2000. Edinburgh, Edinburgh University Press.

SNH . 2015. Scotland's National Peatland Plan. SNH. URL: http://www.snh.gov.uk/docs/A1697542.pdf [Accessed 01/Nov/2015].

Sommers, W. T., R. A. Loehman and C. C. Hardy. 2014. Wildland fire emissions, carbon, and climate: Science overview and knowledge needs. Forest Ecology and Management 317: 1-8.

Stephens, S. L., J. J. Moghaddas, C. Edminster, C. E. Fiedler, S. Haase, M. Harrington, J. E. Keeley, E. E. Knapp, J. D. McIver, K. Metlen, C. N. Skinner, and A. Youngblood. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. Ecological Applications 19:305-320.

Stevenson, A. C., and A. N. Rhodes. 2000. Palaeoenvironmental evaluation of the importance of fire as a cause for *Calluna* loss in the British Isles. Palaeogeography Palaeoclimatology Palaeoecology 164:195-206.

Tàbara D, Saurí D, Rufí C. 2003. Forest fire risk management and public participation in changing socio environmental conditions: a case study in a Mediterranean region. Risk Analysis 23: 249-260.

Taylor, E. S. 2015. Impact of fire on blanket bogs: implications for vegetation and the carbon cycle. University of Edinburgh, Scotland. http://hdl.handle.net/1842/10554

Tharme, A. P., R. E. Green, D. Baines, I. P. Bainbridge, and M. O'Brien. 2001. The effect of management for red grouse shooting on the population density of breeding birds on heather-dominated moorland. Journal of Applied Ecology 38:439-457.

The Ecologist. 2015. Britain's 'protected' moorlands go up in flames. The Ecologist. URL: http://www.theecologist.org/News/news_round_up/2957144/britains_protected_moorlands_go_up_in_flames.html [Accessed 01/Nov/2015].

Thompson, D. B. A., A. J. MacDonald, J. H. Marsden, and C. A. Galbraith. 1995. Upland heather moorland in Great Britain: A review of international importance, vegetation change and some objectives for nature conservation. Biological Conservation 71:163-178.

Thompson, D. K., and J. M. Waddington. 2013. Peat properties and water retention in boreal forested peatlands subject to wildfire. Water Resources Research 49:3651-3658.

Thompson, D. K., B. W. Benscoter, and J. M. Waddington. 2014. Water balance of a burned and unburned forested boreal peatland. Hydrological Processes 28:5954-5964.

Thorp S. 2015. Respect, Trust & Honesty. Available from: http://heathertrust.blogspot.com/2015/07/respect-trust-honesty.html [Accessed 11th February 2016].

Tian, D., Y. Wang, M. Bergin, Y. Hu, Y. Liu, and A. G. Russell. 2008. Air quality impacts from prescribed forest fires under different management practices. Environmental Science and Technology 42:2767-2772.

Tucker, G. 2003. Review of the impacts of heather and grassland burning in the uplands on soils, hydrology and biodiversity. English Nature Research Reports No. 550, English Nature, Peterborough.

Turetsky, M.R., Harden, J.W., Friedli, H.R., Flannigan, M., Payne, N., Crock, J., Radke, L., 2006. Wildfires threaten mercury stocks in northern soils. Geophysical Research Letters 33, doi: 10.1029/2005GL025595.

Turetsky, M.R., W.F. Donahue and B.W. Benscoter. 2011. Experimental drying intensifies burning and carbon losses in a northern peatland. Nature Communications, 2, 514. doi:10.1038/ncomms1523.

Turetsky, M. R., B. Benscoter, S. Page, G. Rein, G. R. van der Werf and A. Watts. 2015. Global vulnerability of peatlands to fire and carbon loss. Nature Geoscience 8: 11–14.

Usher, M. B., and D. B. A. Thompson. 1993. Variation in the upland heathlands of Great Britain: Conservation importance. Biological Conservation 66:69-81.

Vandvik, V., E. Heegaard, I. E. Maren, and P. A. Aarrestad. 2005. Managing heterogeneity: the importance of grazing and environmental variation on post-fire succession in heathlands. Journal of Applied Ecology 42:139-149.

Walker, T. N., M.H. Garnett, S.E. Ward, S. Oakley, R.D. Bardgett and N.J. Ostle. in press. Vascular plants promote ancient peatland carbon loss with climate warming. Global Change Biology, doi:10.1111/gcb.13213

Ward S. E., R. D. Bardgett, N. P. McNamara, J. K. Adamson and N. J. Ostle. 2007. Long-term consequences of grazing and burning on northern peatland carbon dynamics. Ecosystems 10: 1069-1083.

Watts O. 2014. Regular burning of English upland peatlands must stop: new study shows damage much worse than thought. RSPB Website. URL: http://www.rspb.org.uk/community/ourwork/b/climatechange/archive/2014/10/07/regular-burning-of-english-upland-peatlands-must-stop-new-study-shows-damage-much-worse-than-thought.aspx [Accessed 01/Nov/2015].

Wieder, R. K., K. D. Scott, K. Kamminga, M. A. Vile, D. H. Vitt, T. Bone, B. XU, B. W. Benscoter and J. S. Bhatti. 2009. Postfire carbon balance in boreal bogs of Alberta, Canada. Global Change Biology 15: 63-81.

Whitfield D. P., D. R. A McLeod, J. Watson, A. H. Fielding, and P. F. Haworth. 2003. The association of grouse moor in Scotland with the illegal use of poisons to control predators. Biological Conservation 114: 157-163.

Worrall, F., G.D. Clay, R.H. Marrs and M.S. Reed .2010. Impacts of Burning Management on Peatlands. Scientific Review. IUCN Peatland Programme. Available from: http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/images/Review%20Impacts%20of%20Burning%20on%20Peatlands%2C%20June%202011%20Final.pdf [Accessed 11th February 2016]

Worrall F., G. D. Clay, and R. May. 2013. Controls upon biomass losses and char production from prescribed burning on UK moorland, Journal of Environmental Management 120: 27-36.

Yallop, A., J. Thacker, G. Thomas, M. Stephens, B. Clutterbuck, T. Brewer, and C. Sannier. 2006. The extent and intensity of management burning in the English uplands. Journal of Applied Ecology 43:1138-1148.

Zenova, G. M., N. A. Glushkova, M. V. Bannikov, A. P. Shvarov, A. I. Pozdnyakov, and D. G. Zvyagintsev. 2008. Actinomycetal complexes in drained peat soils of the taiga zone upon pyrogenic succession. Eurasian Soil Science 41:394-399.

Table 1: A selection of recent media coverage associated with scientific papers and reports concerning the use of fire on U.K. peatlands. The main quote is the first paragraph of the article. Whilst many of the articles provided some balance by reporting the opinions of a range of stakeholders including those involved in the game industry, few provided an opinion from a non-associated scientist or reflected the uncertainties involved in assessing the complex effects of prescribed burning.

Media title	Main quote	Media reference	Associated paper
"Grouse-shooting popularity boosts global warming"	"The "glorious 12th" falls this weekend. It's the start of the U.K.'s grouse-shooting season, attracting the rich and famous from around the world. But the country will be getting a bigger bang than it bargained for. Attempts to breed more grouse on the moors to meet rising demand are boosting the U.K.'s contribution to global warming."	Pearce (2006)	Yallop et al. (2006)
"Cut heather burning for sake of the environment"	"Ember study suggests muirburning degrades upland moorland, its fauna and flora."	Amos (2014)	Brown et al. (2014)
"Burning debate reignited"	"Heather burning on moorland has "significant negative impacts" on natural habitats, according to a study by academics, claims which have been countered this week by the Moorland Association."	Barnett (2014)	Brown et al. (2014)
" 'Amazon of U.K.' being destroyed for grouse shooting"	"Managing moorlands so that more birds can be reared for lucrative shooting parties is adding to climate change by destroying layers of peat and releasing large quantities of stored carbon dioxide into the atmosphere."	Brown (2014)	Brown et al. (2014)
"Peatlands burn as gamekeepers create landscape fit for grouse-shooting"	"They are home to a diverse range of wildlife and up to 8,000 years old. And, according to a damning analysis by an independent government advisory body, the U.K.'s upland peat bogs are facing a sustained threat from the shooting classes' desire to bag grouse."	Doward (2015)	Douglas et al. (2015)
Burn moor, or less?	An authoritative study has revealed the environmental effects of moorland burning. The	Hart (2014)	Brown et al. (2014)

	Effects of Moorland Burning on the Ecohydrology of River basins project (EMBER), adds to a debate over grouse moor management		
"Why we should rewild the British uplands"	"The upland environment covers a third of Britain. It is a cherished landscape, close to the hearts of most of us. Much of this landscape is within National Parks celebrated for their 'natural beauty'. Yet, for the most part, whilst they are beautiful, they are a far way from a natural environment. They are overgrazed sheep pastures and burnt grouse moors. "	Manighetti (2015)	Brown et al. (2014)
"Feeling the heat from peatland vegetation burning"	"There are more than 1.5 million hectares of peatlands in the U.K., covering 17.2 per cent of the land surface. Upland moorlands face a range of management pressures in the U.K., and recent research shows vegetation burning in peatlands has altered the biodiversity of their rivers. "	Ramchunder (2013)	Brown et al. (2014)
Burning of heather 'damaging peatlands and rivers'	"The tradition of burning heather on sporting estates causes significant environmental damage to both peatlands and nearby rivers, according to a new authoritative scientific study. "	Ross (2014)	Brown et al. (2014)
"Regular burning of English upland peatlands must stop: new study shows damage much worse than thought"	"Every big scientific project needs a good acronym these days and the Leeds University team hits the spot with EMBER - Effects of Moorland Burning Ecohydrology of River basins. And in line with the acronym, the results show that the damage that burning heather has on wildlife, climate change and the environment is far worse than previously thought, and more wide ranging - water run-off from burned peat harms aquatic life in the rivers that spring from these uplands. In short, managed burning has a profound impact on the life support systems of the peatlands in our hills."	Watts (2014)	Brown et al. (2014)

"Moorland burning 'threatens protected landscape'"	"It is a traditional tactic used over the decades to regenerate the stunning moorland landscapes that attract thousands of visitors to the region every year but an old debate over its contribution to wildlife conservation has been re-ignited"	Barnett (2015)	Douglas et al. (2015)
"Shooting industry must stop putting strain on countryside, says RSPB chief"	"More than 50 million game birds a year are being released for shooting, putting increasing strain on native wild birds and the ecology of the UK's countryside, landowners will be warned on Friday. "	Davies (2015)	Douglas et al. (2015)
"Britain's 'protected' moorlands go up in flame"	"A new study led by RSPB shows that more than half of Britain's most precious upland moors are suffering from burning - widely used to increase the numbers of red grouse available for recreational shooting."	The Ecologist (2015)	Douglas et al. (2015)
"Moorland report criticises heather burning"	"The practice of scouring moorland by burning off heather has left many conservation areas in Scotland in a poor condition, a charity has said"	Harrison (2015)	Douglas et al. (2015)
"Protest against grouse shooting on Ilkley Moor"	"A protest will take place this morning against controversial grouse shooting on Ilkley Moor. The event at Bradford City Hall coincides with the opening of the burning season, when moorlands are set on fire to increase game bird numbers for shooting."	ITV (2015)	N/A

Box 1: Guidance from Common Standards Monitoring (JNCC 2009) for the condition of protected areas in the United Kingdom. Note that, in each case below, point two (no signs of burning or other disturbance) essentially covers all areas of blanket bog or wet heath dominated by *Sphagnum* and areas of blanket bog with abundant pleurocarpous and acrocarpous mosses. This means that not only can an area with *Sphagnum* not be in good condition if it shows any sign of being burnt, but areas of blanket bog not dominated by *Sphagnum* cannot be burnt either. Oddly, according to these standards it would not matter if a manager had burnt an area with a bare peat substrate.

With regards to burning, to be in "good condition" the following conditions must be met in blanket bog habitats:

1. There should be no observable signs of burning into the moss, liverwort or lichen layer or exposure of peat surface due to burning.
2. There should be no signs of burning or other disturbance (e.g. mowing) in the following sensitive areas:

- Ground with abundant and/or an almost continuous carpet of *Sphagnum*, other mosses, liverworts and/or lichens.
- Areas with noticeably uneven structure, at a spatial scale of around 1 m^2 or less. The unevenness should be the result of *Sphagnum* hummocks, lawns and hollows, or mixtures of well-developed cotton-grass tussocks and spreading bushes of dwarf-shrubs.

For wet heath habitats to be in "good condition", the following conditions must be met:

1. There should be no observable signs of burning into the moss, liverwort or lichen layer or exposure of peat surface due to burning.
2. There should be no signs of burning and other disturbance inside the boundaries of the "sensitive areas" which includes ground with abundant, and/or an almost continuous carpet of *Sphagnum*, liverworts and/or lichens. This target should also be recorded if any evidence of this is found while walking between sample locations.

Figure 1: Some examples of moorlands managed through traditional prescribed burning associated with grouse moor management. Prescribed burning creates a range of changes in peatland ecosystems including a range of ecosystem benefits. Burning practice varies widely across the U.K. in terms of spatial extent and frequency. Depending on how fires are managed the visual and aesthetic impacts can be greater or lesser. All images from geography.org.uk. Bottom right, a typical low severity prescribed burn moving through the lower canopy of a stand of *Calluna vulgaris*, the moss and litter layer covering the peat surface is left more-or-less untouched.